ACOUSTIC, ELECTRON AND OPTICAL MICROSCOPY VISUALIZATION OF SURFACE AND SUB-SURFACE CRACKS

Z. M. Connor, M. E. Fine, and J. D. Achenbach

Center for Quality Engineering and Failure Prevention
Northwestern University
Evanston, IL 60208

INTRODUCTION

The purpose of the present study was to carefully document the early stages of fatigue damage in flush head riveted Alclad 2024-T3 aluminum alloy panel specimens. The fatigue cracks originate and initially propagate below the surfaces that are observable by optical and electron microscopy. Acoustic microscopy images such cracks and was employed to follow the observable sub-surface growth of fatigue cracks. In addition the cracks were monitored on the observable surface by optical and electron microscopy both in-situ and ex-situ during and after the test was completed. Careful fractographic analysis of the fracture surfaces was also done and correlated with the microscopic observations. The specimens used in this study were fabricated according to the specifications for the fuselage of an aircraft, and these specimens were not precracked or notched.

Many studies have been done on the fatigue of aluminum panels with drilled holes or drilled and countersunk holes [1-3] and on the fatigue of riveted specimens or actual fuselages[4-11]. These studies of riveted specimens or actual fuselages have been somewhat limited because the fatigue cracks were not examined nondestructively until they reached the visible surface of the panel. The availability of the acoustic microscope enables us to study these subsurface cracks before they reach the visible surface.

Initial research in this laboratory was performed on specimens consisting of a flat panel of Alclad 2024-T3 aluminum alloy with a countersunk hole.[2] In these specimens, fatigue cracks initiated at the knife edge of the countersunk hole and close to the centerline of the hole as predicted by fracture mechanics theory. In riveted lap joints; however, the stress state is much more complex. When the joint is riveted, a residual compressive stress is introduced. The lap joint experiences a bending stress when it is loaded because of the asymmetry of the joint. Furthermore, the load is transferred between panels through the rivets.

As shown by earlier research in this laboratory on riveted panel specimens, the fatigue cracks initiated on inner surfaces not available for optical or electron microscopic examination. The cracks initiated on the back surface of the countersunk panel containing the rivet head and some distance away from the “knife edge”. Surface damage in the form of microcracks and plastic strain markings has been observed to be a precursor to the emergence of a growing crack on the outer surface of the countersunk panel. [4, 5]

EXPERIMENTAL PROCEDURES

Each lap joint specimen was assembled from two Alclad 2024-T3 aluminum alloy panels, 1.02 mm thick, using 2017-T4 aluminum alloy rivets following a Boeing specification [12]. The specimen geometry and dimensions are given in Figure 1. The chamfered rivets were 3.97 mm in diameter in the stem and 6.35 mm in length. The rivet head was approximately 6 mm in diameter. The cladding on the 2024-T3 panels was 1050 aluminum alloy, 0.05 mm thick on each side. Each specimen contained three rivets oriented in line parallel to the loading direction and were 25.4 mm apart in this direction. One panel in each pair making up the specimen had countersunk rivet holes and one had straight holes. The three hole panels were 38 mm wide by 121 mm long, and after riveting 165 mm long. The holes and countersinks were drilled with a computer controlled machining center. The straight through hole diameters were between 4.04 mm and 4.09 mm. The limits for the hole diameter given in the Boeing specification are between 4.04 mm and 4.24 mm, with the smaller diameter being favored. [12, 13] The included angle of the countersink was 100°. The depth of the countersink was gradually increased until a knife edge of 0.20 mm ± 0.01 mm was obtained. This gives a knife edge of

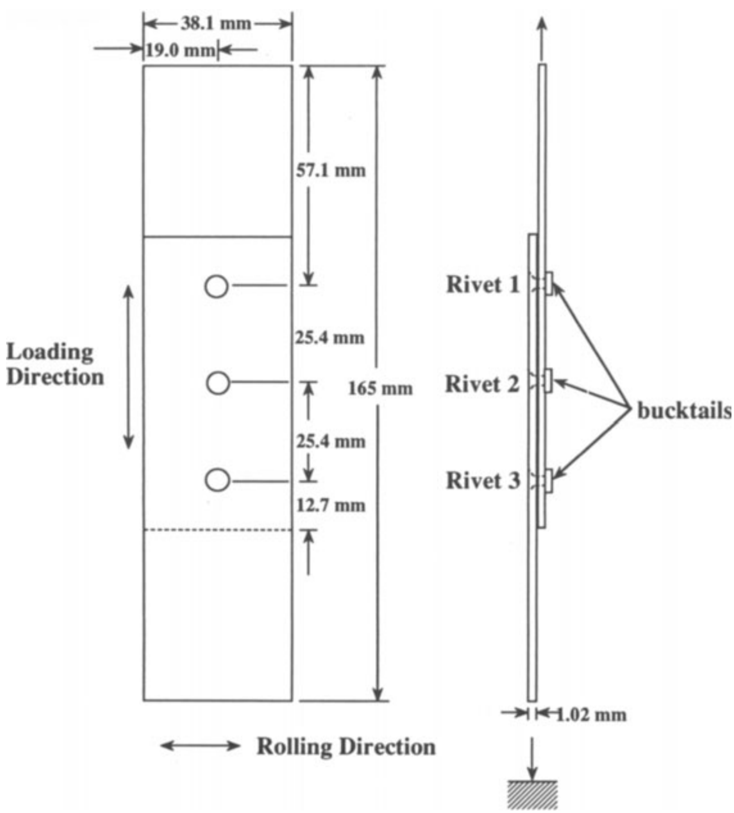

Figure 1. Drawing of three rivet assembled specimen.

approximately 20% of the thickness of the panel. Typical flushness requirements for the rivet heads in aircraft panels, +0.102 mm to -0.000 mm., were met by the specimen geometry [13].

The panels were riveted together on a manually operated hydraulic press by compressing between two flat plates at a constant load of 44.6 kN. This load was used to obtain a bucktail diameter of 6.12 mm ± 0.05 mm in accordance with Boeing Company 737 Structural Repair Standard (1970). [12]

The specimens were fatigue loaded in uniaxial tension and tested in load control using an MTS Machine (comparable to an MTS 810 system) with a maximum load of 4.0 kN and an R ratio of 0.1. This load was selected on the basis of preliminary experiments to give failure in several hundred thousand cycles. [4] Neglecting the rivet hole (which is filled with the rivet and in a state of compression) and using the cross sectional area of one panel, the nominal stress was 103 MPa for those specimens tested at a maximum load of 4.0 kN. Shims of the same thickness as the panels were placed in the grip sections to center the load axis with the center line of the specimen.

The flush head riveted specimen surface (outside surface) was observed during the tests with an Olympus microscope (Model 225143) at a magnification of 40x. This microscope was mounted with an x-y micrometer base on the MTS machine so that observations of plastic deformation and surface breaking microcracks and strain markings (rumpling) could be made and later propagating crack lengths measured without removing the samples from the MTS machine. Many tests were continued until failure, but many tests were stopped much earlier in the fatigue process, and the specimens were examined more carefully with other microscopes in a metallography laboratory as well as by scanning acoustic microscopy. Plastic replicas were taken on some of the specimens at intervals during the testing. The replicas were taken with the specimens loaded at 80 percent of the maximum load so that the cracks would be open and the replicating material would penetrate into the cracks. Crack growth measurements of surface breaking cracks using optical microscopy were obtained on six specimens. Some specimens were disassembled by grinding off the bucktail and carefully separating the plates. Then all surfaces were microscopically examined.

Specimens at various stages in the fatigue process that had already been carefully examined with optical microscopes were further examined using a scanning acoustic microscope (SAM) to obtain C-scan images of the specimens. [5] A focused transducer with a center frequency of approximately 50 MHz was used in conjunction with a Panametrics Hyscan system. [14] The specimens were submerged in a tap water tank for examination. The focused transducer, attached to x, y, z stages, was excited by a Panametrics Pulser-Receiver (Model 5601A/ST) to generate ultrasonic waves. The focused beam was reflected by the specimen and returned to the transducer which then acted as a receiver. The transducer output signals, digitized by a Tektronix TDS-540 four channel digitizing oscilloscope and processed by a Panametrics Gated Peak Detector (Model 5608) were then acquired by a personal computer to produce a C-scan image. The signal reflected from the back surface of the plate with countersunk rivet holes was maximized, and then the transducer was defocused to give the best image of the crack. This signal was gated, and its peak value provided the data for the C-scan image. Acoustic microscope C-scan images reveal two dimensional projected images of cracks located throughout the specimen thickness.

For those specimens which were investigated using the SAM, plastic replicas and acoustic scans were generally taken at the commencement of the fatigue test and at intervals during the fatigue test. Crack lengths on the acoustic scan images were measured vs. number of cycles.

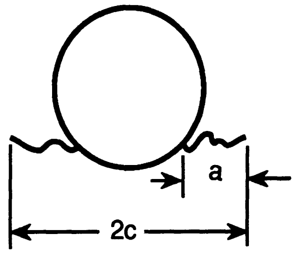

Figure 2. Drawing defining the crack length.

The testing of three specimens was stopped after cracks were observed in the acoustic scans. These specimens were disassembled and the inner panel surfaces were examined. The specimens were then fractured by pulling them in tension at peak fracture loads of 10 to 11 kN.

RESULTS AND DISCUSSION

Using the optical microscope, the first indication of fatigue damage on the outer surface of the specimens was surface rumpling consisting of plastic deformation markings and microcracks. This surface rumpling appeared near (but not always at) the rivet head of Rivet 3 identified in Figure 1. The appearance of the rumpled region is the first indication on the outer surface of the existence of a subsurface crack. Detection of the rumpled region by an NDE technique may be an opportunity to detect fatigue damage before a propagating crack appears on the outer surface.

The approximate number of cycles until a propagating radial crack emerged on the outer rivet head panel surface was defined as N_{ao}. The average N_{ao} in six specimens was 263,000 cycles. Observations were made every 10,000 cycles. The crack, when first seen, was only on one side of the rivet. It was already 0.5 to 1.7 mm long on the outer surface, (a in Figure 2). The variation in initial optically observed crack size on the outer surface of the panel arises in part because the initial cracks are sub-surface, take different paths to reach the surface and initially propagate rapidly on the outer surface once they have broken through. The average number of cycles to an 8 mm long crack extending on both sides of the rivet, (2c) as defined in Figure 2, was 302,000 cycles. Thus approximately 87% of the cycles to an 8 mm (end to end) long crack are spent generating a surface breaking radial crack on one side of the rivet. Some of this data was presented in an earlier paper. [4]

The resolution of a microscope can be defined as the minimum size of a feature that can be determined. An expression for the resolution of the reflection acoustic microscope is given in Ref [15] as:

$$\omega = \frac{0.51\lambda_o}{N.A.} \tag{1}$$

where N. A. is the numerical aperture and is equal to sin θ_0 where θ_0 is the semi-angle subtended. The wavelength, λ_0, is given by v_0/f, where v_0 is the velocity of sound in the fluid and f is the frequency.

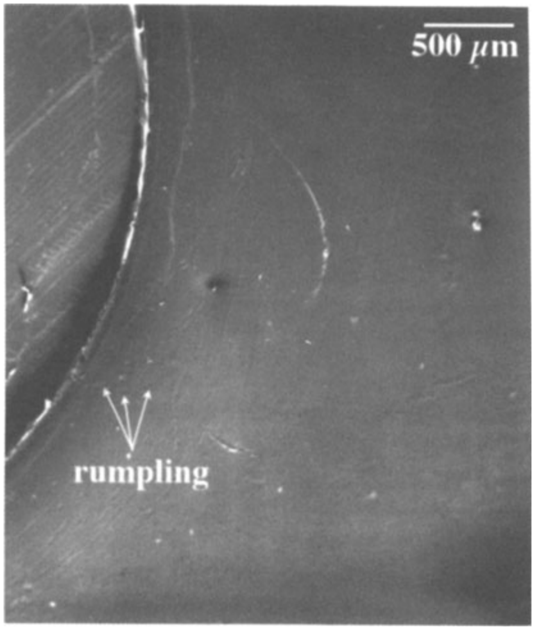

Figure 3. Surface rumpling as seen in a scanning electron micrograph of the plastic replica of a specimen at 195,000 cycles.

The center frequency of the transducer used in these experiments is about 50 MHz. The velocity of sound is 1531 m/sec in sea water and 1496.7 m/sec in distilled water, giving wavelengths of 3.06×10^{-2} mm and 2.99×10^{-2} mm respectively. Estimating θ_o to be between 5° and 10° gives a resolution between 88 μm and 175 μm for distilled water and between 89 μm and 179 μm for sea water. From this a conservative estimate of the resolution of the acoustic scans is between 90 μm to 180 μm.

The average number of cycles until a crack was observed in the acoustic scans of five three-rivet specimens, defined as N_{as}, was found to be 192,000 cycles. The number of cycles between the first observance of a crack on the acoustic scans and the observance of surface rumpling was 55,000 cycles in a specimen where a crack was first observed on the right side in an acoustic C-scan at 140,000 (Fig. 4) while the surface rumpling from this crack (Fig. 3) was first observed at 195,000 cycles. The test was stopped after 205,000 cycles and the specimen was disassembled. A scanning electron micrograph of the fracture surface is shown in Figure 5. The inside arrows in the micrograph correspond to the crack length at 140,000 cycles and the outside arrows correspond to the crack length at 205,000 cycles both as viewed in the acoustic scan. The initiation sites, as determined from the radial marks, are indicated by the letter "I" in the micrograph. Notice that when the sample was disassembled the crack had not yet reached the surface of the panel on either side.

Another specimen was fatigued until a short crack was seen in the acoustic scan and then the specimen was disassembled and pulled apart. The fracture surface of this specimen revealed that this short crack had not yet reached the surface of the panel and also had not even reached the rivet hole.

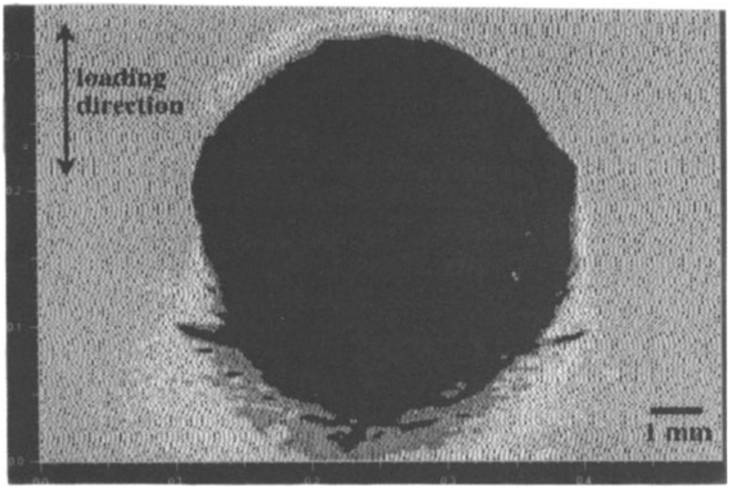

Figure 4. Subsurface cracks as seen in the C-scan of the same specimen as shown in Figure 3 after 195,000 cycles.

SUMMARY AND CONCLUSIONS

Fatigue cracks which initiate near rivets in riveted lap joints form in the subsurface region of the outer panel, that is the panel with the rivet head and propagate for some distance before they break the outer surface, the surface available for visual examination. The acoustic microscope in the C-scan mode images such subsurface cracks allowing them to be detected much earlier in the fatigue life than by visual inspection of the outer surface. The average number of cycles until a crack was observed in the acoustic C-scans was found to be 192,000 cycles while the average number of cycles until a propagating radial crack on the rivet head panel surface was seen to have emerged was found to be 263,000 cycles. The average number of cycles for an 8 mm crack to form was found to be 302,000 cycles so that 87% of the life to an 8 mm crack is taken in forming a surface breaking crack, while 63% of the life to an 8 mm crack is in forming a crack which is detectable by the acoustic microscope. In one specimen, the difference between the number of cycles between the first observance of a crack on the acoustic scans and the first observance of surface rumpling, which is an indicator that there is a subsurface crack, was 55,000 cycles.

The growth rates for small subsurface cracks is much slower than that for small surface breaking cracks. Since the subsurface crack length is longer, the trace of the crack on the surface tries to catch up.

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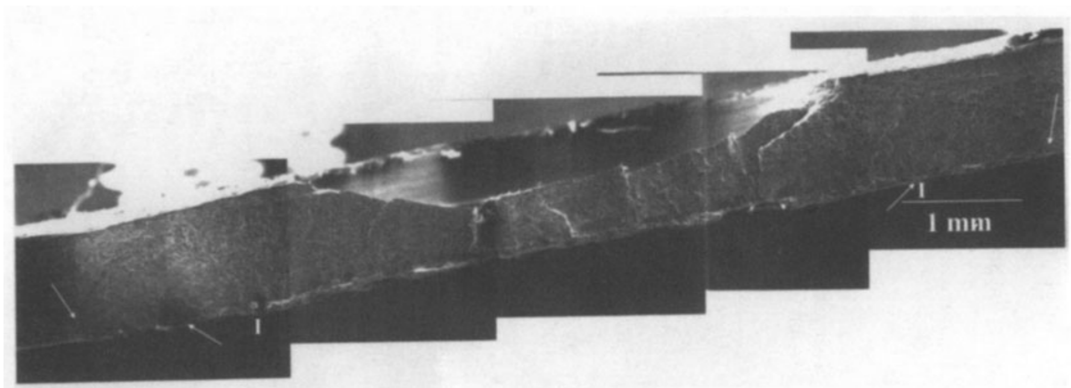

Figure 5. Fracture surface of the specimen shown in Figures 3 and 4 after 205,000 cycles.

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